# A new stylus instrument with a wide dynamic range for use in surface metrology

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*An instrument has been developed which can measure not only radius of curvature but also form deviation and surface texture at the same time. A computer is used to mathematically separate the form from the texture. The technique can be applied to the measurement of cross track curvature of bearing raceways and to other precision components whose form is defined as a circular arc, or a straight line, in which case angle will be measured instead of radius. The measurement of other forms such as parabolic, elliptical, hyperbolic and aspheric are the subject of continuing development. The instrument provides a distinctive and useful advance in measurement by the stylus method, offering possible solutions to many obdurate problems in the field of surface metrology*

**Keywords:** surface roughness measurement, form tolerances, curved, transducers

In modern technologies, the assessment of performance of a component in respect of its various physical specifications[1] is often dependent on a comprehensive measurement of component surface topography. Two essential aspects of this are its form and texture which hitherto have required separate assessments, often with interdependent error.

Conventional surface finish instruments have a measuring range of typically 0.1 mm, but are adapted to the measurement of texture of a curved component by matching a curved datum to that component. The method is tedious and time consuming and never gives the exactitude derived by a comprehensive assessment supported by the analysis of a digital computer.

In order to acquire the data for this comprehensive analysis, a pick-up with a wide dynamic range is essential because of the disparate amplitudes of form and texture. This type of comprehensive assessment is now feasible by a new stylus instrument which incorporates a digital transducer with a wide dynamic range.

Setting up to measure a curved component is considerably simplified, reducing the complete measurement cycle time to typically less than one minute. Component form is separated from the surface texture mathematically in the calculation of its various dimensional parameters which describe the form.

Applications include the measurement of circular formed components such as ball bearings, bearing raceways, diamond turned mirrors and diamond turning tools.

## Pick-up

To measure the form, surface texture and radius of the component depicted in Fig 1 in a single traverse, a pick-up is needed which can measure in the $y$ direction with a range

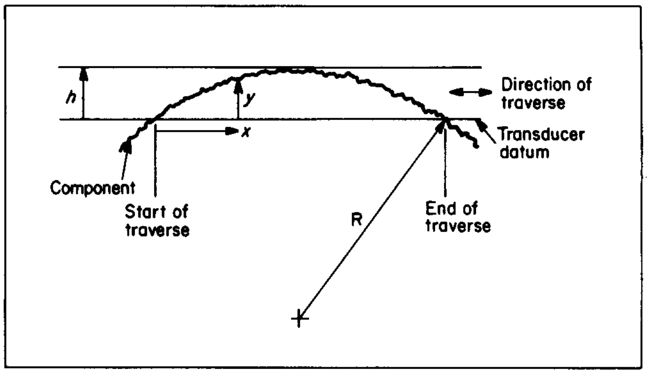


*Fig 1 Co-ordinate system used in the assessment of both form and texture of a curved surface*

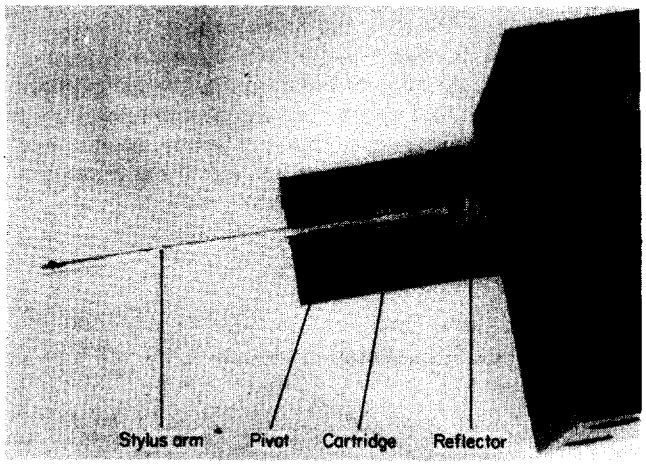


*Fig 2 Pick-up cartridge of the new instrument*

of at least $h$ and a resolution high enough to detect the surface texture detail. Accurate measurement of the pick-up traverse, in the $x$ direction, is essential.

The pick-up comprises a pivoted lever, on one end of which is the stylus which contacts the surface to be measured, and on the other end is a reflector. This acts as the measurement arm of an interferometric transducer[2] to give a direct digital output with a measuring range presently of 2 mm, a resolution of 5 nm and a frequency response of about 300 Hz. The interferometer and stylus arm are housed in a 30 mm diameter cartridge (Fig 2).

The light source for the Michelson type interferometer is a commercially available helium-neon laser of 1 mW output and wavelength $\lambda$. The output beam from the interferometer, derived from both measurement and reference arms, is split into four, enabling four photodiodes to detect the fringe pattern. These signals, indicating the stylus displacement $y$, are fed into a preamplifier board producing the conventional quadrature signals which enable bidirectional counting and interpolation to $\lambda/128$[3]. This gives a range to resolution ratio of $5 \times 10^5$, ie equivalent to 19 bits.

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Fig 3 shows the transducer and a traversing unit which provides the accurate $x$ axis traverse.

Certain factors must be taken into account when using a transducer with these capabilities, described as follows.

## *Transducer linearity*

The stylus arm pivot has a precise axis of rotation which introduces minimal friction and allows for the wide measuring range. The variation in static stylus force over this range is also minimal. These constraints help to ensure that the stylus arm moves accurately over the wide range. However, the normal assumption of linearity of stylus movements will no longer apply in either the $y$ or the $x$ directions, and a small correction is made by the computer for the cross axis relationship of the pick-up geometry.

The corrected $y \simeq Ay + By^2$, where $A$ is nominally 1 and $B = a/2b^2$ and horizontal stylus movement $x \simeq Cy - Dy^2$, where $C = a/b$ and $D = 1/2b$, and where $a$ is the distance from the stylus tip to the stylus arm and $b$ is the distance from the stylus to the pivot.

## *Stylus arm vibration and sampling interval*

Any unwanted resonance in the stylus arm of an analogue transducer is usually controlled in design to be well outside the frequency range of the instrument; it is therefore 'lost' before digitising. This is not so for the case of a digital transducer and its effect must be 'lost' by digital filtering.

To satisfy the Nyquist criterion, the sampling interval must be less than half the shortest wavelength present in the signal, otherwise aliassing will occur. The arm resonance in this instrument design is to be at 350 Hz. The traversing table holding the workpiece has a velocity of 1 mm/s, giving the resonance a wavelength of 2.85 $\mu$m. This may be assumed to be the shortest wavelength of interest, in which case a data sampling interval of 1.4 $\mu$m or less is required.

The stylus tube is constructed from aluminium alloy for lightness, but this material has a low damping ratio. Hooker[6] states a value as low as 0.0001, which would give a sustained amplitude of vibration when excited. This has been increased to about 0.1 in this instrument, by the application of a visco-elastic damping material[6].

This damping helped to reduce the vibration amplitude which was further reduced by the use of a digital notch filter, the characteristics of which give zero transmission at a wavelength of 3 $\mu$m and 70% at 6 $\mu$m.

The use of a carbon fibre stylus arm is considered valuable in this context.

## *Digital sampling of the data*

The sampling of data in a digital system may be controlled temporally or spatially. The use of temporal sampling to measure the $x$ direction in Fig 1 is not advisable, as any speed fluctuations in the traverse give related errors $E$ in the sampling distance. Referring to Fig 1, if the best fit arc was calculated using temporal sampling and then subtracted from the data, the resulting surface detail would show this error with amplitude $e = E \tan a$, where $a$ is the angle at which the stylus is traversing (ie the tilt of the component being measured) relative to the true datum of the instrument. To avoid this, spatial sampling is employed which is more reliable, though less convenient.

The motion of the traversing table (Fig 3) is measured by a Michelson interferometer. A 1 mW laser unstabilised in frequency, is attached to the rear of the traversing table,

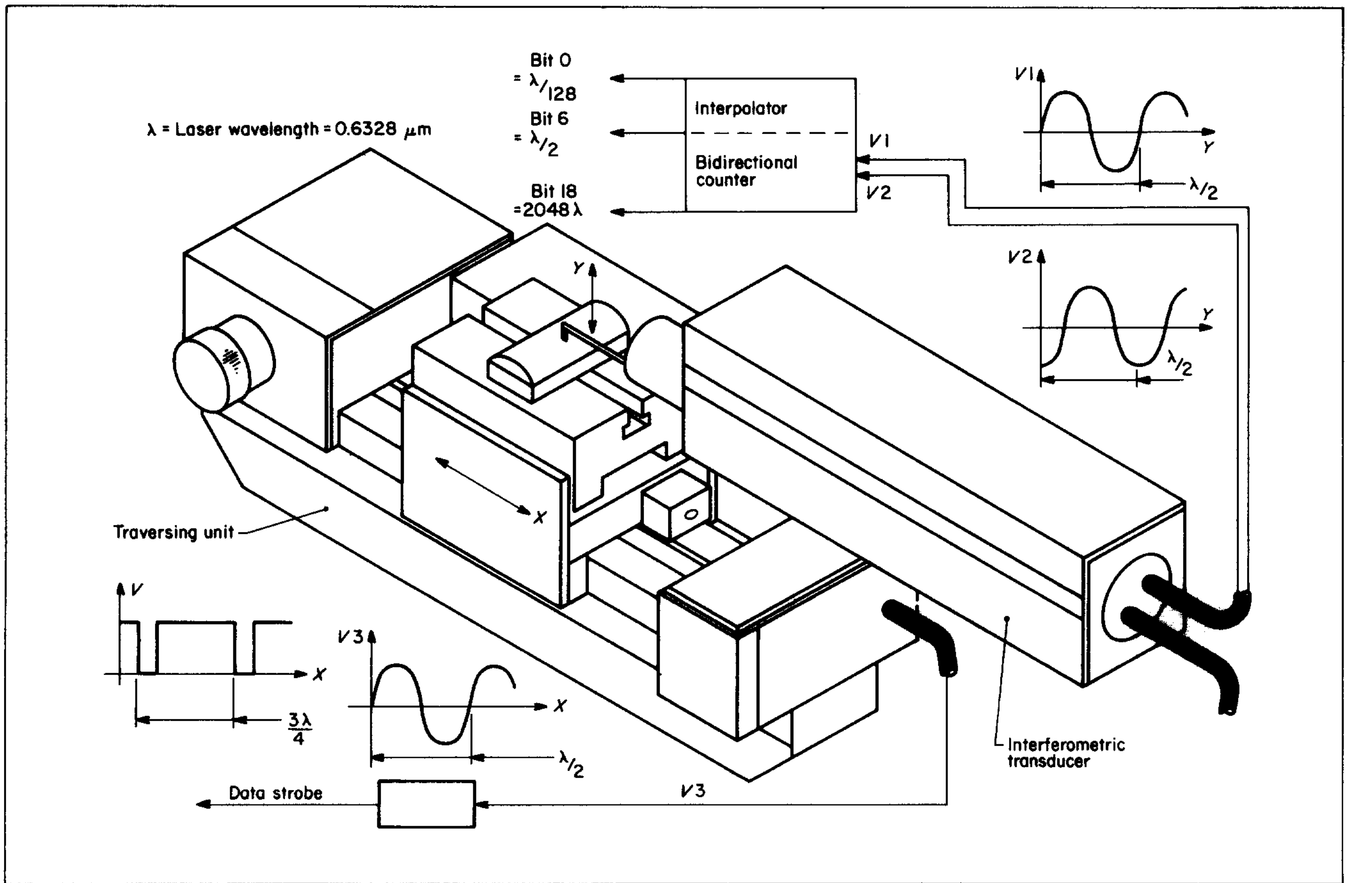
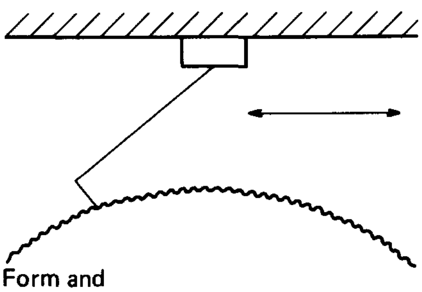
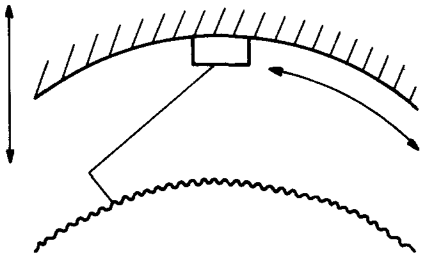
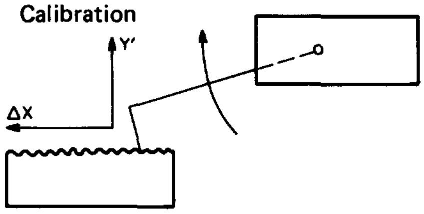
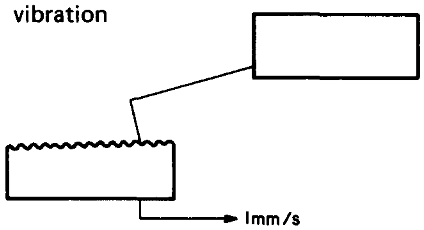



*Fig 3 New instrument*

**Table 1 Comparison between a stylus instrument incorporating a conventional analogue transducer and one incorporating the new digital transducer**

| Digital transducer | | Analogue transducer |
|---|---|---|
| 2.59 mm | Range | 0.1 mm |
| 5 nm | Resolution | 5 nm |
| $5 \times 10^5$ (19 bits) | Usable range/ resolution ratio | $10^3$ (10 bits) |
|  Form and texture | Curve measurement |  Form or texture |
| $y' = Ay + By^2$<br>$\Delta x = Cy + Dy^2$ | Calibration   | $y' = Ay$ |
| Wavelength = 2.85 $\mu$m<br>Data sampling $\leqslant$ 1.4 $\mu$m<br>Damping<br>Digital filtering | Stylus arm vibration   | Beyond frequency range of instrument |

providing the light source for the interferometer which is positioned in the lower end block. The mirror for the measurement arm is attached to the carriage table, as near as possible to the vertical measuring plane of the interferometric transducer to reduce offset error in accordance with the Abbe principle.

With a traverse length of 150 mm, the coherence length of the laser is adequate because the position for zero path difference occurs when the table is at its mid-traverse. Two photodiodes detect the fringe pattern, and hence the movement of the table. The resultant signals are fed to a preamplifier and signal conditioner located near to the interferometer, to produce a data sampling pulse every 0.4746 $\mu$m, which satisfies the Nyquist criterion.

### *Comparison of digital and analogue transducer characteristics*

A comparison between a stylus instrument system incorporating a conventional analogue transducer and the one incorporating the new digital transducer which has been described above, is summarised in Table 1.

## The instrument system

Fig 4 shows a view of the system with a schematic layout in Fig 5. This is built around a standard Rank Taylor Hobson product, Talydata, embodying a Data General microNova computer. Nineteen of the logic inputs are used for the data of the interferometric transducer. The dac provides an analogue signal to the recorder. Instrument operation is controlled by the handheld console, responding to 'menu' messages displayed on the vdu.

### *Reference lines and calibration*

Considering the component in Fig 1, to accurately fit a reference line conforming to a best fit circular arc[4,5] to the data collected by the transducer, a calibration routine is required in respect of constants of the individual geometry of the pick-up. It is not sufficient to use calibration standards of the step height or average ($R_a$) type. A round, smooth, ball of known radius is traversed under the stylus. After the best fit arc has been calculated and subtracted from the data, the modified data should show minimum form error and the calculated radius should agree with the true radius of the ball, enabling the calibration referred to under 'Transducer linearity' above to be achieved.

This calibration is absolute and will be true for other measurements whether the reference line is a circular arc, a straight line, or any other curve. The accuracy in radius measurement or parameter of any curve depends mainly on the calibration accuracy, traverse length chosen, and the surface texture present.

The stylus tip has the form of a truncated pyramid and has a finite dimension (about 2 μm); its value has to be taken into account as it passes the valley on a concave component, or the peak on a convex component.

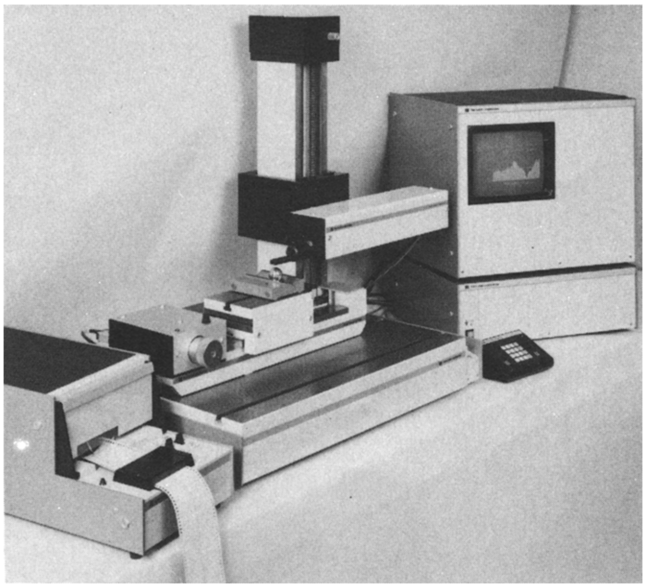


*Fig 4 Complete system*

The stylus is not always normal to the surface being measured; the inclination has to be compensated to give valid form error and surface finish height information. The stylus included angle is 90°, therefore, if the contact angle between stylus and surface approaches 45°, measurements will become inaccurate.

When the best fit is calculated, the ordinate spacing is based on the chord of the arc; after the arc has been subtracted, the residual data are referred to the arc itself, to give valid form error and surface finish wavelength information.

Similar corrections are necessary if a straight line reference is used to remove large angles of tilt when measuring a flat component. The accuracy of the measured angle of tilt of the straight line reference again depends on the calibration accuracy, traverse length chosen and the surface texture present.

## *Surface texture measurement*

Surface texture comparisons were made between a Taylor-Hobson Talysurf 4 instrument and the new instrument, by measuring a fine turned surface with a high harmonic content.

For each measurement, three traverses were taken over similar sections of the component and the results averaged. Each traverse yielded 1000 ordinates at 2 μm spacing. A best fit least squares straight line was subtracted from the sets of data and further modified by a standard 2CR high pass filter with a 0.25 mm cut-off to obtain the surface texture parameters and power spectrum shown in Fig 6.

The new instrument has a low wavelength limit, but as this is very near to the stylus tip size, it will have a minimal effect on measurements taken over general engineering surfaces. Good correlation is indicated between the

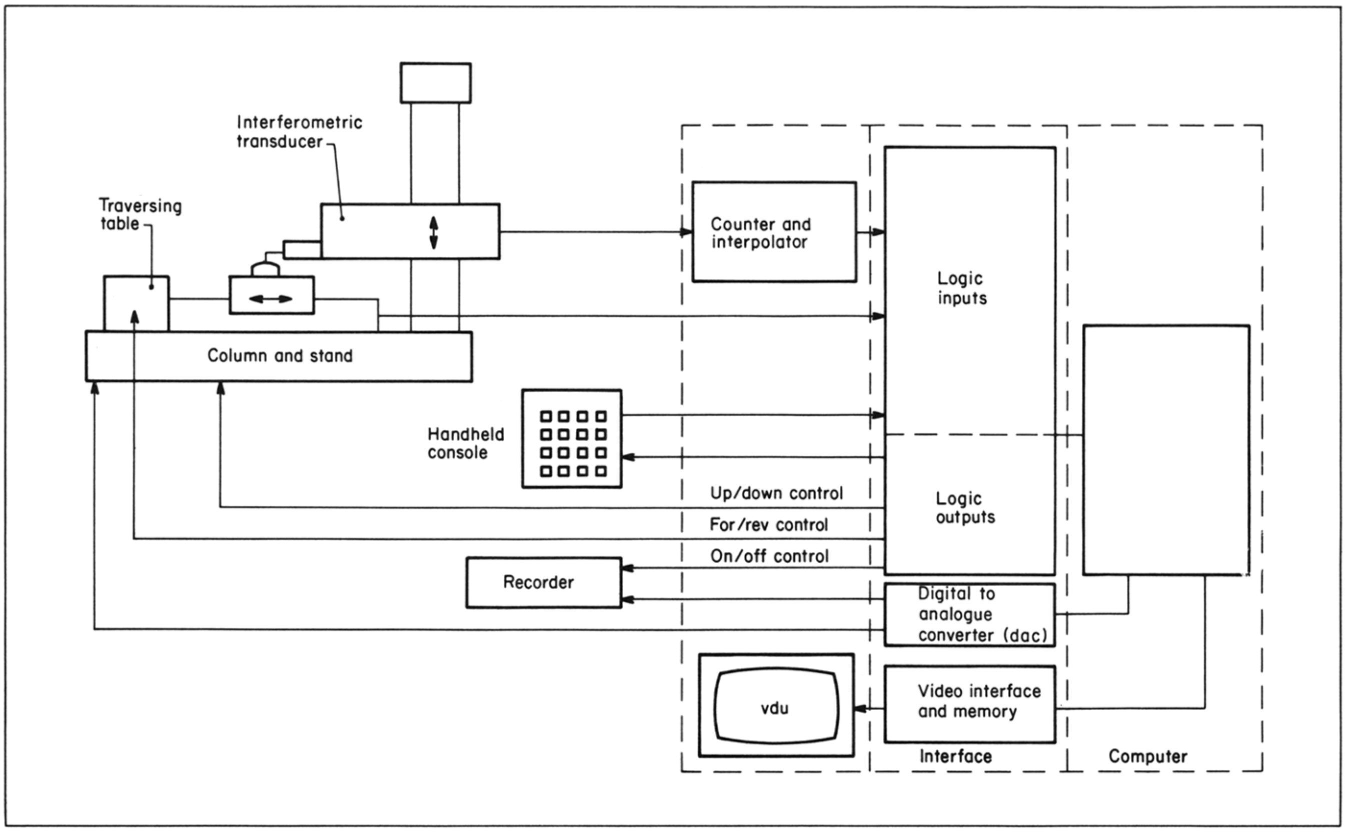



*Fig 5 Complete system*

Turned surface

0.25 mm ISO filter cut-off

| Instrument | Talysurf | New | | |
|---|---|---|---|---|
| Tilt, ° | 0.01 | 0.1 | 19 | 32 |
| Power spectrum | | | | |
| $R_t$, µm | 1.45 | 1.54 | 1.62 | 1.49 |
| $R_a$, µm | 0.262 | 0.262 | 0.260 | 0.263 |
| $\Delta_a$, ° | 3.12 | 3.02 | 3.03 | 3.12 |
| $\lambda_a$, µm | 30.2 | 31.2 | 30.9 | 29.9 |

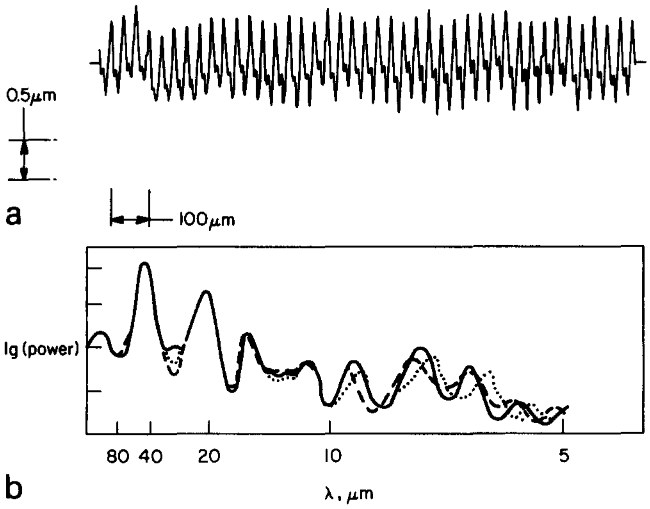



*Fig 6 Comparison between Talysurf and new stylus instruments on surface measurements (a) filtered profile and (b) power spectrum*

measurement from both instruments, even when the component surface has a large tilt, relative to the instrument's datum. Four filtered profile traces could not be distinguished.

## Applications

Fig 7 shows a measurement over a $\phi$25.4 mm ball. The profile contains the form errors and texture after the best fit arc has been subtracted from the data. The peak to valley (P-V) is taken over the assessment length $L$ (P-V) and the $R_a$ and $R_q$ values are taken over $L$ ($R_a$), the difference in these lengths being the settling distance for the filter, typically twice the cut-off.

The ball was used to calibrate the instrument, and all applications described in this section were taken with respect to this one calibration.

### *Ball bearings*

An important application is the measurement of cross track curvature of bearing raceways. One traditional method of measuring the radius is to project the arc onto the screen of an optical comparator at an appropriate magnification and compare it to arcs drawn on a template. This method has a number of disadvantages, one being that the measurement is subjective and depends on operator interpretation.

Fig 8 shows results of a bearing raceway measurement; Fig 8(a) shows the whole cross-section including lands, after the best fit line has been subtracted. The same data are used for obtaining the results shown in Fig 8(b), where a best fit arc is subtracted from the circular part of the raceway to display the form errors and surface texture.

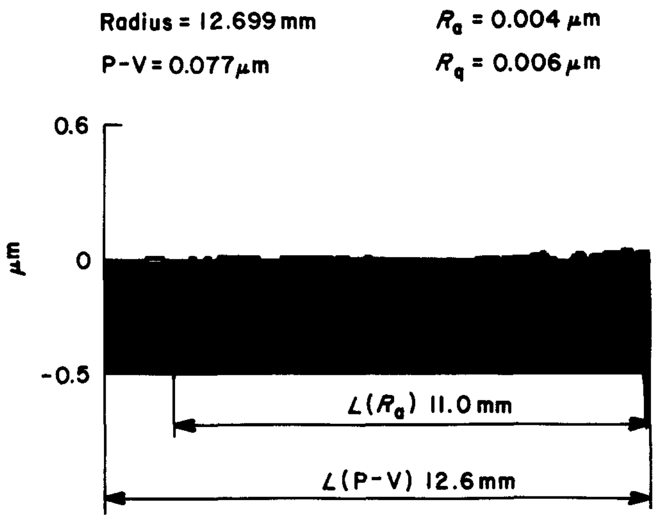



*Fig 7 Measurement of $\phi$25.4 mm ball*

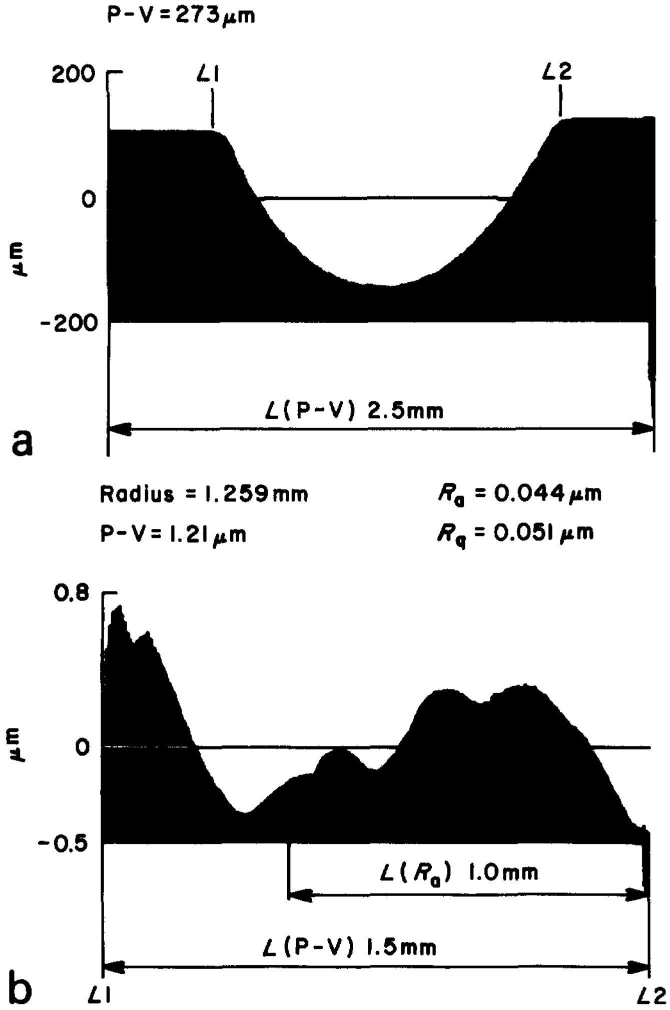



*Fig 8 Measurement of cross track curvature on bearing races (a) with best fit line subtracted and (b) with best fit arc subtracted*

The range of radii of interest is usually between 0.4 mm and 20 mm. The measurement accuracy on radius has been found in practice to be generally better than 3 µm for this range.

Further applications include the measurement of the balls (Fig 7) and rollers that make up the rest of the bearing.

## *Optical components*

Diamond turning is becoming highly important in the manufacture of mirrors and some lenses. The traditional method of measurement is by interferometry, with problems of interpretation and setting-up. This technique cannot be used for many modern types of infra red lenses.

Fig 9 shows the measurement of a diamond turned mirror with a hole through its centre. Figs 9(b) and 9(c) show measurements taken over assessment lengths *L*1 and *L*2 respectively. There is a harmonic error in the machining process which is clearly shown in the measurement. Also note the expected relationship between form errors of the left and right hand traces. The radii of interest are usually between 20 mm and 600 mm with a measurement accuracy of radius better than 0.1% of the nominal value.

The diamond tools that are used to generate these surfaces can have an arcuate cutting surface. Fig 10 shows a measurement of such a tool after the best fit arc has been subtracted. Fig 10(a) is the tool as new, whereas Fig 10(b) is the same tool after many cuts have been taken, hence the slight wear on one side of the cutting edge, shown encircled in Fig 10(b).

Fig 11 shows measurements of both a concave and convex glass gauge of the same radius after the best fit arc has been subtracted. The difference in measured radii could be accountable to the stylus size and shape, but the measurement is still within the specification of the instrument. Many optical components are highly polished and have $R_a$ values better than 0.008 $\mu$m, which is approaching the noise level of conventional instruments. Fig 11(a) shows an $R_a$ value of 0.003 $\mu$m for the concave glass gauge, which demonstrates the low noise limit of the instrument.

Aspheric mirrors and lenses could also be measured. With the best fit arc subtracted, the resulting asphericity will be displayed. Where the asphericity is large, it will not be easy to measure small asphericity deviations unless reference is made to the aspheric form. However, if this deviation is not of interest, high pass filtering will enable the surface finish detail to be obtained.

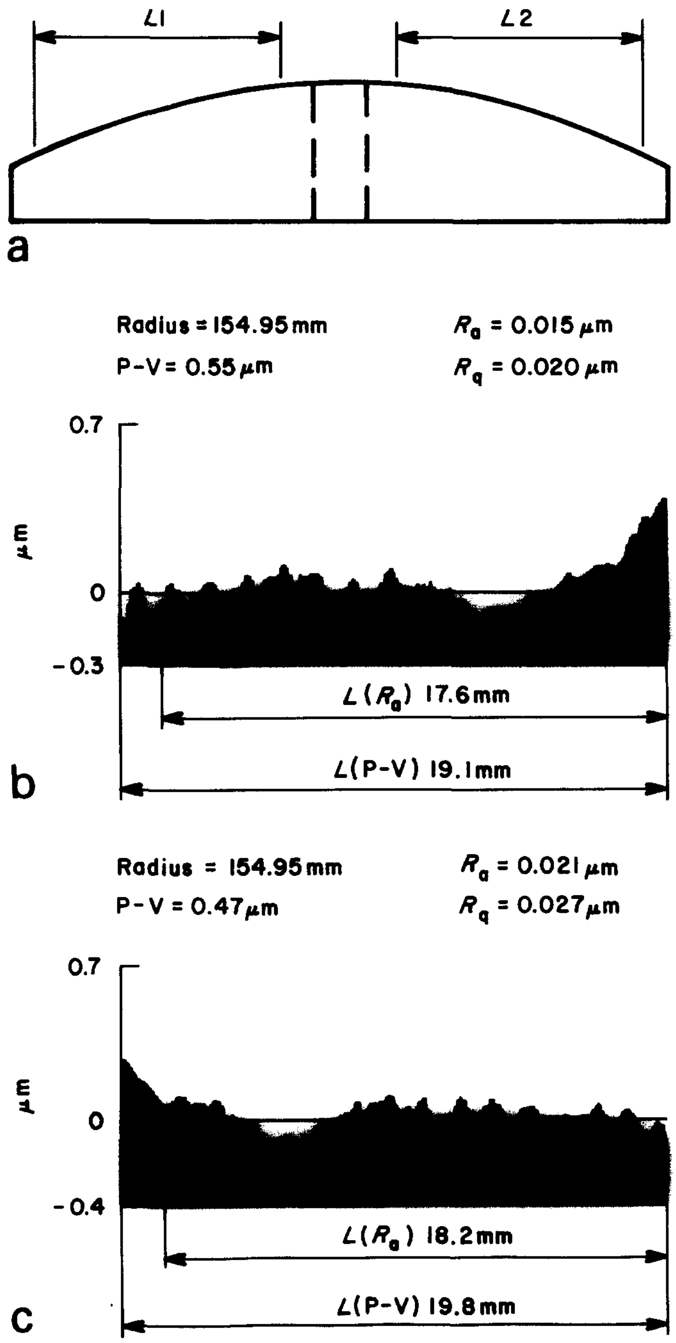



*Fig 9 Measurements of a diamond turned mirror (a) cross-sectional view, (b) form and texture over L1 and (c) form and texture over L2*

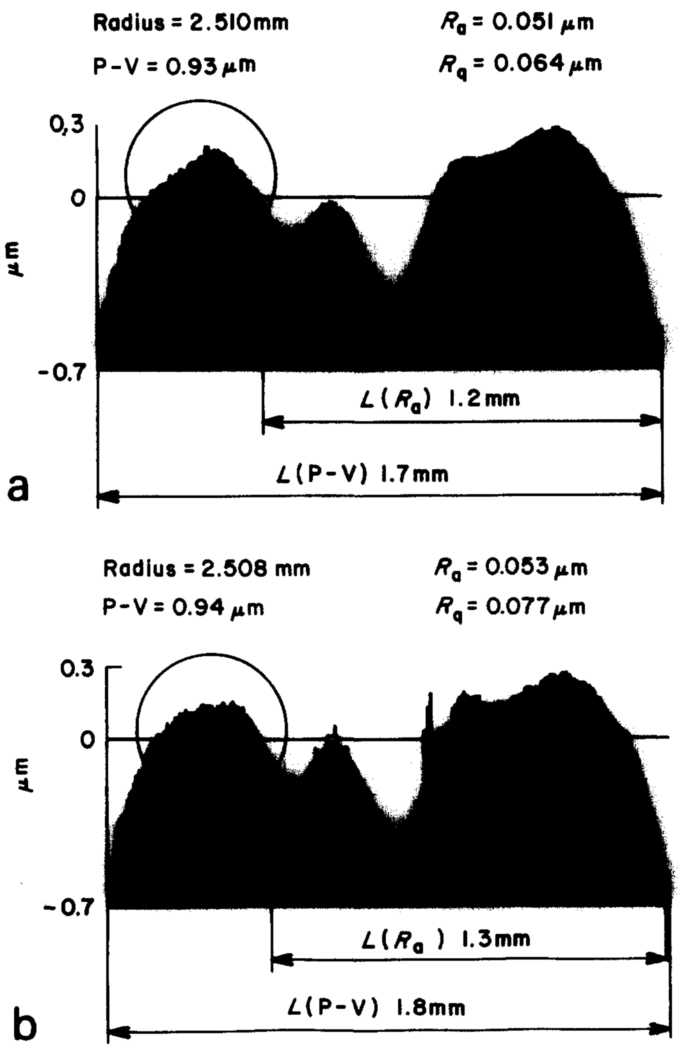



*Fig 10 Measurement of a diamond turning tool, (a) new tool and (b) tool, showing wear*

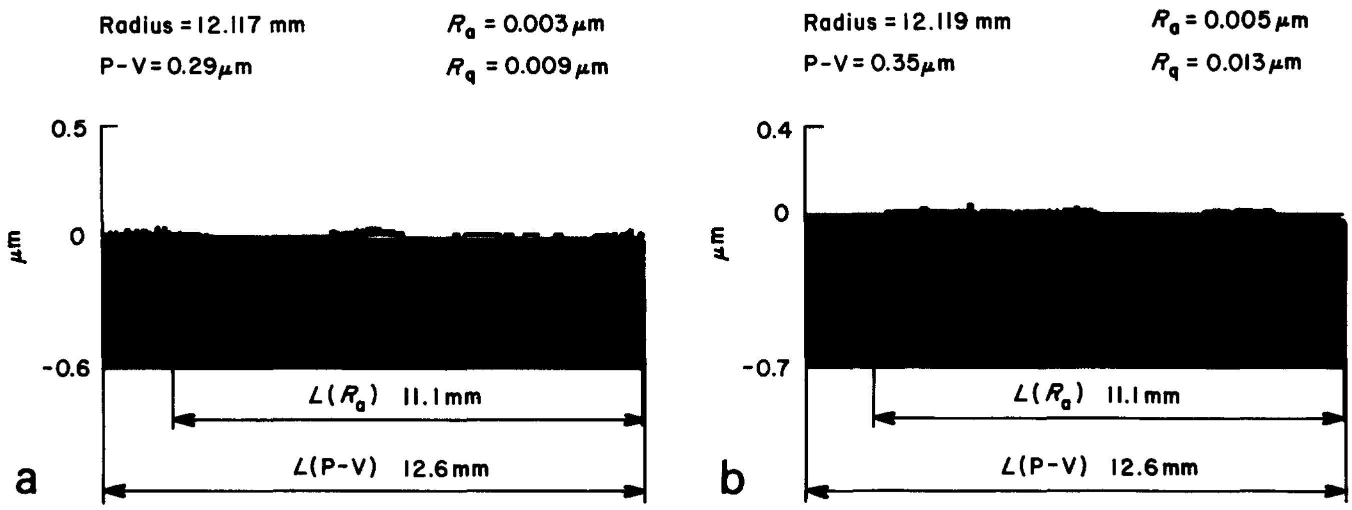



*Fig 11 Measurement of glass gauges of radius 12.116 mm. (a) Concave gauge and (b) convex gauge*

### Acknowledgements

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# PRECIS

## Measuring system interface

Introduction of the interface adapter, PE 2585, it is claimed, now enables the Philips MK IV Linear Measuring System to be universally employed for machine tool control.

The MK IV measures accurately the traverses on machine tools, translating the movements into electrical control signals by means of a dynamic opto-electronic conversion and a solid state transducer.

The adapter enables the system to be interfaced simply and speedily to various types of control system. With wide mounting tolerances, the complete apparatus is ideally suited as original equipment for fitting by oem's to new machine tools, or for retrospective addition to existing ones.

The opto-electronics system consists of a measuring head and scales. These are reflection scales, glass rulers coated with an aluminium grating, their graduation marks each 635 μm wide.

Each glass ruler is bonded to a chromium steel base for mechanical protection. As chromium steel has the same thermal expansion coefficient as cast iron, the material from which most machine tools are constructed, the accuracy of the mounted measuring system is not affected by temperature variations.

Scales are available in 240, 480, 720 and 960 mm lengths, mounted either on massive flat bases or on square-section tube. The mounting systems are so designed that they can be fitted on most machine tools with minimum modification. Scales of different lengths can be combined in any way desired, the maximum measuring length being theoretically unlimited. In addition to the two standard types of scale, there is also a special precision flat-base scale, also available in four lengths.

The transducer (PE 2580) scans the scales and converts the displacement information into an electrical position signal which can be processed by the associated control or digital readout. Because the transducer functions on the dynamic principle by means of the opto-scanner, it permits very high interpolation so that, in spite of the coarse scale grating, a resolution of 0.5 μm (interpolation factor 1270) or 0.000 05 in (interpolation factor 500) can be achieved.

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## Talyrond 200

Comprehensive measuring capabilities of the Talyrond 200, used in the measurement of roundness and straightness, are described in a brochure from Rank Taylor Hobson Ltd. These range from those offered with the basic Talyrond 200 to more advanced analyses available with Talydata 1000 microcomputer backed systems. Programs for roundness, harmonic and slope, and cylindricity analyses are explained with accompanying illustrations. There is also a section on all-embracing piston measurement with the most up-to-date Talyrond 200 systems.

A selection of accessories is also described and a number of applications are illustrated.

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